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Minority Ion Measurements During ICRF Experiments in Alcator C-Mod

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Abstract. ICRF is the primary auxiliary heating in C-Mod where both H or ^{3}He minority and mode conversion regimes are utilized. For transport analysis, the power deposition profile is critical and measuring the resulting fast ion distribution provides a direct means to constrain and validate ICRF simulations used to calculate power deposition. In mode conversion, measurement of the minority ion density, temperature, and velocity profiles is critical for the wave physics and may provide some insight into the fundamental physics of flow drive. Using active charge exchange, the He^{+1} 4686Å or H 6563Å line is observed to find whether fast ion and relevant thermal ion measurements are practical. Results of these experiments yield fast ion and thermal ion measurements in D(He). A new analysis technique to extract information from high noise fast ion spectra is developed. A development path for improved D(^{3}He) and D(H) is indicated.

Keywords: ICRF, fast ions, energetic particles, CXRS, CHERS, FIDA, RF heating
PACS: 52.50.Qt, 52.55.Fa, 52.40.Fd, 52.70.Kz, 52.70.-m, 52.40.Mj

INTRODUCTION

Fast wave injection in the ion cyclotron range of frequencies (ICRF) is the primary auxiliary heating method in Alcator C-Mod where both H or ^{3}He minority and mode conversion regimes are used. In those cases, charge exchange recombination spectroscopy (CXRS) of the minority species using a diagnostic neutral beam provides both measured information regarding the fast ion distribution and density, temperature and flow velocity of the thermal component of the minority species. These are predicted by the simulation of minority heating (MH) scenarios and the measurements therefore constrain the simulations.

ICRF power is coupled to the plasma via one 4-strap antenna and two 2-strap antennas [1]. The 4-strap antenna is frequency tuned to place the fundamental minority resonance in the core for either H or ^{3}He minority. An equilibrium reconstruction for a D(^{3}He) experiment described here is shown in Figure 1. The position of the ^{3}He fundamental resonance is shown as a vertical dash-dot line. To acquire the CXRS data, a 50 keV, 6 A H neutral beam is injected at an angle of approximately 6° to a major radius from the low field side by the diagnostic neutral beam injector [2] as shown by the green shaded region in Figure 1. The CXRS poloidal views are in red. The CXRS toroidal views projected onto the poloidal cross section are in blue. Other aspects of the CXRS diagnostic are discussed in detail in reference [3].

Radio Frequency Power in Plasmas
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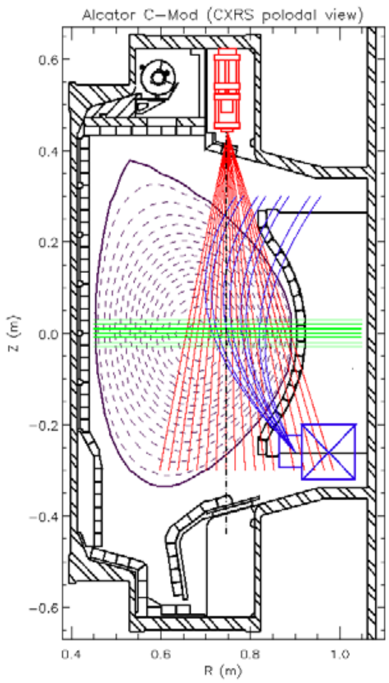

FIGURE 1. Poloidal section of the vacuum vessel, CXRS viewing chords, and ^{3}He ICRF resonance.

The CXRS diagnostic is the focus of this report. It differs from that previously described [3] principally in that it has been modified to measure emission from the minority species. For D(H) plasma (minority in parentheses), the basic charge exchange and emission processes for thermalized species are in eqn. 1. The corresponding processes for thermalized species in the D(^{3}He) plasma are in eqn. 2. The spectral volume emission is given by the eqn. 3 which is used for simulation of measurement and for the synthetic diagnostic in the ICRF simulation. In (3), n_i is the beam density for the ith energy component, $f(v)$ is the minority ion distribution function, σ is the effective cross section leading to photon emission, and the delta function represents the Doppler effect. Halo effects are included by artificially introducing a 0 energy beam component. The detection of fast ions follows just the same prescription with the thermal plasma ions replaced by the non-thermal ions generated by the RF absorption.

$$H^{+}_{\text{plasma}} + H^{0}_{\text{beam}} \rightarrow H^{*}_{\text{plasma}} + H^{+};\; H^{*}(n=3) \rightarrow H^{*}(n=2) + h\nu(6582A) \qquad (1)$$

$$He^{+2}_{\text{plasma}} + H^{0}_{\text{beam}} \rightarrow He^{*+}_{\text{plasma}} + H^{+};\; He^{*+}_{\text{plasma}}(n=4) \rightarrow He^{*+}_{\text{plasma}}(n=3) + h\nu(4686\,A) \qquad (2)$$

$$\varepsilon(\lambda)\mathrm{d}V\mathrm{d}\Omega = \frac{1}{4\pi}\sum_i n_i \int f(\vec{v})\sigma\left(\tfrac{1}{2}m\left|\vec{v}-\vec{v_i}\right|^2\right)\delta\left[\lambda-\lambda_0\left(1+\frac{v\cos\alpha}{c}\right)\right]\mathrm{d}^3v \qquad (3)$$

RESULTS

For the required hydrogen measurement in D(H) plasmas, cold D_α emission from the deuterium fuel overlaps with the hydrogen fast ion emission but is much brighter due to its higher concentration. To achieve adequate signal to noise, an interference filter with a steep high pass edge near 6580 Å was used to attenuate the deuterium and the thermal hydrogen emission but leave the emission from a high energy population of fast ions relatively unaffected. The measured spectrum is shown in Fig. 2. The spectrum contains contributions from bremsstrahlung, beam emission, thermal deuterium, thermal hydrogen, and impurity lines in addition to the desired contribution from fast hydrogen ions.

The fast ion spectrum was simulated by inserting a Stix distribution [4] into equation 3, integrating over beam width, and making corrections for Stark and Zeeman effects.

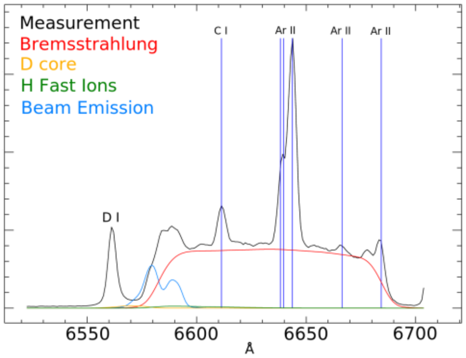

FIGURE 2. Measured spectrum from a poloidal channel for D(H) plasma.

The complexity of the spectrum in Figure 2 motivated a decision to concentrate on D(^{3}He) plasmas which does not limit the planned research but which avoids many of the interfering emission sources. For helium, no interference filter was used, and the entire line is fitted. A simulated ^{3}He spectrum is shown in Fig. 3 and illustrates the critical need to model the non-thermal portion of the emission, the spectral wings. Due to the limited signal to noise in this proof-of-principal experiment, a conservative fitting model was used to analyze the fast ion distribution. A Pearson type VII distribution (or Student's T distribution) is used (eqn. 4). For large *m*, the distribution approaches a Gaussian (thermal) distribution. A smaller value for *m* generates a non-thermal distribution with the required higher density wings. Thus, *m* becomes a proxy for the fast ion component present in the minority population. This appears to be the first use of this technique for overcoming the ubiquitous S/N problem by measuring the entire line wing with such a simple but accurate approach.

$$p(x) \propto \left[1+\left(\frac{\lambda-\lambda_0}{\alpha}\right)^2\right]^{-m} \tag{4}$$

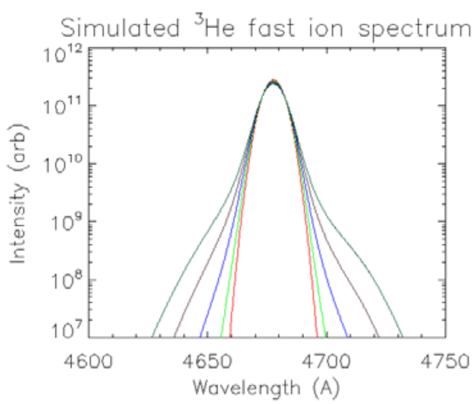

FIGURE 3. Simulated ^{3}He emission for five values of RF power (0, 0.83, 1.7, 2.5, 3.3 kW/cm^3)

Evidence for fast ions was observed in a D(^{3}He) plasma, with $n_{He}/n_e \approx 3\%$, when 4 MW of ICRF power was applied. Figure 4 shows the kurtosis over over time segments with and without ICRF. When ICRF power is applied, the kurtosis or departure from a thermal distribution is marked and at the appropriate location in the plasma.

Density measurements require absolute calibration of the intensity. Four calibration methods are available and applied consistently with the experimental constraints. The methods are: calibration with a radiometric standard; detection of emission from helium gas excited by a hydrogen beam; interpretation of continuum spectra as pure bremsstrahlung; and comparison of CXRS measured helium ion density with measured electron density in a helium plasma.

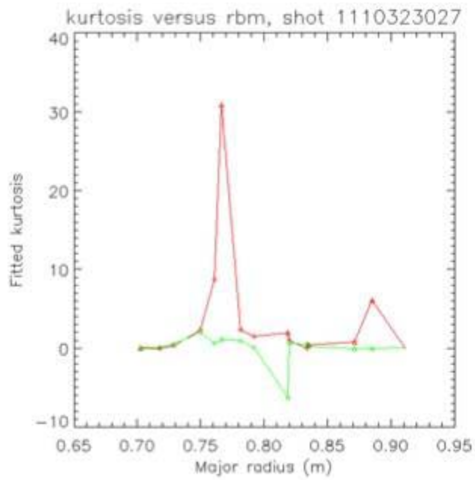

FIGURE 4. Evidence of fast ions was found using the CXRS system. The fitted line shapes exhibit an increased kurtosis near the IC resonance.

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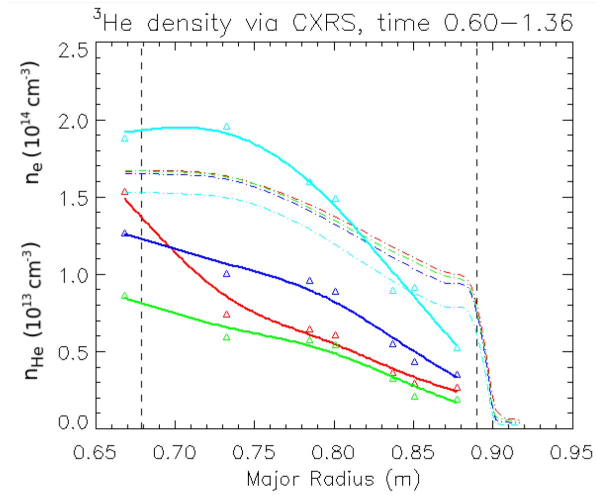

FIGURE 5. Sample helium density profiles for the ICRF experiment. Solid lines show smoothed profile; dotted lines show electron density

PLANS

To improve the signal to noise for the D(H) experiments, a blocking bar optical element [5] will be added. The advantage over the interference filter used for the same purpose here is that a steeper cutoff can be applied, and both wings of the spectrum can be observed. Signal to noise will improve.

The helium fast ion measurement will also improve with addition of the blocking bar. Exceptionally good detection and strong emission even at low helium concentration allow use of a grating with higher dispersion. Fast ion and temperature measurement sensitivity will increase with this new grating. With these improvements, the research will move quickly from this diagnostic development phase to an experimental phase.

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